

NAG5-3783: Determining the compositions of extraterrestrial lava flows**Summary of Research**

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Research Objectives

The primary purpose of this research project has been to develop techniques that allow the emplacement conditions of volcanic landforms on other planets to be related to attributes that can be remotely detected with available instrumentation. The underlying assumption of our work is that the appearance of a volcano, lava flow, debris avalanche, or exhumed magmatic intrusion can provide clues about the conditions operating when that feature was first emplaced. Magma composition, amount of crustal heat flow, state of tectonic stress, and climatic conditions are among the important variables that can be inferred from the morphology and texture of an igneous body.

Approaches and Projects

In this research we have used a combination of approaches, including field mapping and remote sensing observations of terrestrial volcanic features, laboratory simulations of flow processes, and theoretical and numerical modeling of flow emplacement and stress states in volcanic systems. Over the past several years we have systematically investigated a wide variety of factors influencing the eruption of lava flows and domes, and the intrusion of dikes, including: 1) the relative importance of cooling and eruption rate and magma composition on flow morphology and texture; 2) the role of eruption history (episodic, continuous, variable) on the aspect (height to diameter) ratios of domes and flows; 3) the effect of underlying slope and external confinement on the dynamics and morphology of cooling flows; 4) the impact of vesicular and glassy textures on thermal infrared characteristics of silicic lavas; 5) the influence of dissolved water on the ability of lava domes to undergo explosive collapse, and 6) volcanic stress states and dike emplacement. All of these studies have attempted to constrain the compositions or eruption rates of lava flows on Mars, Venus, the Moon, and Earth, or the state of tectonic stress in the crust underlying these extrusions. These investigations have allowed us to develop and evaluate morphologic and structural criteria for the remote determination of the rheology, composition, and emplacement histories of volcanic constructs.

Progress and Results

1) Magma composition

During our most recent grant period, much of our progress has been in the conduct and interpretation of laboratory simulations of lava morphology. We analyzed a previous set of approximately 250 polyethylene glycol (PEG) wax simulations to evaluate how flow width and lava flow surface structures vary with eruption conditions, and applied results to lavas on Mars, Venus, and the Moon (Gregg and Fink, 1996, 1997; Gregg et al., 1998).

This earlier wax modeling suggested that the morphology and dynamics of many lavas, especially basalts, are controlled by the strength of a cooled carapace that develops during flow away from a vent. In order to better capture the behavior of silicic lavas for which cooling is supplemented by a significant internal yield strength, we developed a new analog system consisting of PEG mixed with kaolin powder to form a temperature-dependent Bingham slurry that has an isothermal yield strength coupled with a surface carapace that thickens and strengthens with cooling. These runs produced morphologies that differ substantially from those formed of PEG alone, and more closely resemble features seen in natural lava domes. With increasing cooling, flows acquired shapes that we refer to as *axisymmetric*, *platy*, *lobate*, and *spiny* (Griffiths and Fink, 1997; Fink and Griffiths, 1998). There is also a progression of surface textures accompanying increased cooling (or decreased flow rate): surface block sizes become larger and differential movement along fractures becomes more prominent. As was the case for our previous experiments with PEG alone, transitions between these groups may be defined with a single dimensionless number, which we refer to as Ψ_B , where the subscript B denotes a Bingham rheology. We applied these results to venusian "pancake" domes and concluded that their morphology is most consistent with basaltic andesite composition, to domes on Europa to estimate a range of eruption effusion rates and magma compositions, and to prehistoric terrestrial flows to calculate paleo-eruption rates (Griffiths and Fink, 1997; Fink and Griffiths, 1998; Schwarz et al., 1998; Lyman et al., in review).

In addition to these studies of single composition flows, we have worked on the development of an analytical model of magma mixing that considers the introduction of a hot magma enclave into a cooler magma (Blake and Fink, 2000). This model compares the effects of heat transfer (acting to solidify the enclave) and viscous shearing from flow of the host magma (acting to deform and disperse the enclave), and uses the Peclet number (the ratio of thermal and deformation timescales) and a dimensionless rigidification parameter θ to determine how quickly the enclave will "rigidify." The size, shape, and deformation of enclaves in an erupted magma may be used to understand thermal and fluid dynamic processes that occur during magma mixing. Laboratory experiments of polyethylene glycol wax droplets in cold water were used to confirm the analytical model.

2) Eruption history

Although certain models allow lava flow morphology to be related to average eruption rate, available observations indicate that in most eruptions, effusion rates vary continuously, first increasing steadily and then decreasing. In order to explore how effusion history influences the shapes of volcanic constructs, we conducted a series of PEG experiments with a

computer-controlled pump that can be continuously adjusted to produce increasing or decreasing eruption rates, defined in terms of the exponent, α , $V=St^\alpha$. $\alpha<1$ means that eruption rates steadily decrease, while $\alpha>1$ indicates increasing rates. V represents total volume erupted; for constant effusion rate, $S=Q$ and $\alpha=1$. Increasing α leads to progressively taller constructs, which implies that initial eruption rates have a greater influence on the aspect ratio of a construct than later conditions. Early slow effusion allows cooling to dominate spreading, guiding later growth and preventing diameters from increasing further. These results may be applied to individual lava domes and other volcanic constructs like the venusian "pancakes" and submarine seamounts on Earth (Fowler and Fink, 1997; Fowler, 1997). They may also be used to evaluate the eruption histories of fields of adjacent volcanoes, if one considers all of the members of the group to represent stages in the emplacement of a single extrusion.

3) External factors: slope and confinement

Work by Fink and Griffiths (1998, 1990 *JFM*) simulated lava flow formation on flat or gently sloping surfaces, using PEG wax or kaolin slurry experiments. Expanding on these experiments, we have analyzed over 280 simulations of wax lava flows emplaced on slopes varying from 1-60 degrees and found that increasing the slope up to 30 degrees has the same effect on flow morphologies as increasing the effusion rate or decreasing the cooling rate (Gregg and Fink, 2000). This allows characteristic flow morphologies to form at lower Ψ values than for flows emplaced on a flat surface. For slopes between 40-60 degrees, we found there is a slight increase in transitional Ψ values with slope, which may be attributed to gravitational stresses overcoming the solidified wax strength. We have further extended this work by conducting approximately 100 experiments to evaluate the influence of slope on the morphology of flows of high strength slurries representing more silicic lava flows, and found similar morphologic transitions as in the PEG experiments (Lyman et al., 2000; Lyman et al., in review). In addition to these laboratory experiments, we have begun numerical modeling of lava domes on slopes with a series of finite element models with variable lava geometries (length, height, flow front shapes) and underlying slope, in order to analyze stresses within the lava and determine where fractures are most likely to form, resulting in failure of the dome. For the simple elastic case with a given dome geometry (elongate down slope), as the slope increases, the maximum tensile stress moves from the front of the dome upslope towards the base and increases in magnitude (Lyman, 2001). We have also developed thermal finite element models of flows on slopes to analyze the development of lava flow crust with time (Koenig et al., 2001).

Confinement, or channelization of a lava flow, leads to enhanced cooling of the flow margins, which affects the textural development, overall shape, and style of advance of the lava. We have conducted laboratory and theoretical modeling of the effects of channelization on the morphology and dynamics of lavas in glacial and periglacial environments, and mapped features formed by lava/ice interaction at Mt. Rainier and South Sister (Lescinsky and Fink, 1996, 2000; Lescinsky and Sisson, 1998). The underlying premise of this work is that in most cases, lavas are unable to melt glaciers with which they come in contact and thus become confined by them. Our research suggests that enigmatic "long lava flows" (planetary lava flows up to 500 km in length and less than 10 km in width) may be the result of shallow topographic depressions controlling the direction, width and thickness of lava flowing on gentle slopes (Lescinsky and Fink, 1999). The walls of these depressions serve to confine the

lava flow, promoting increased flow thickness and preferential budding directions parallel to the down slope direction of the depression. Increased flow thickness reduces the surface area available for heat loss and viscous drag. To test the ability of subtle topography to control orientations and morphologies of lava flows, we conducted a series of approximately 40 wax laboratory simulations of lava flowing on gentle slopes in a tank with a shallow depression. During our experiments, leveed and folded flows (analogous to aa and fluid pahoehoe flows, respectively) spread to fill the depression and then inflated higher than the depression walls. Inflation and flow thickening were most pronounced in folded flows, which more than doubled the wall height. Periodically, flow buds would overtop the walls and travel a short distance outside of the depression and then stop. This was most pronounced along the outer wall of the channel bend where buds extended several cm from the depression wall. Rifted and pillowed flows (analogous to stiff pahoehoe to pillow lava, respectively) were less affected by external confinement.

4) Vesicularity and thermal infrared remote sensing

In ongoing studies of thermal infrared (TIR) characteristics of silicic lavas, we have found that vesicularity and devitrification tend to mask signatures of silicate compositions (e.g., Ondrusek et al., 1993, *JGR*). Therefore, we must consider lava textures to correctly interpret the chemistry of martian lavas when analyzing data from instruments like the Mars Thermal Emission Spectrometer (TES). Thermal infrared emissivity spectra of a lava surface can be deconvolved to produce an estimate of the vesicularity using a deconvolution approach that models the photon interactions (Ramsey and Fink, 1999). Variations in surface texture on silicic flows can range from dense glass to highly vesicular pumice and are related to emplacement time, volatile content, and internal structure. The use of thermal infrared remote sensing is uniquely sensitive to compositional, textural, and thermal changes. The ability to remotely map surface vesicle percentage has implications for explosive dome hazard mitigation on Earth and the derivation of vesicle and dust distributions on the surface of Mars. In order to derive the changes in surface vesicularity from TIR emissivity, we have studied airborne Thermal Infrared Multispectral Scanner (TIMS) and MODIS-ASTER simulator (MASTER) data of terrestrial domes such as Medicine Lake volcano, CA and the basaltic flows of Mauna Ulu, Kilauea, HI, and conducted calibration field studies to better understand complicating factors such as weathering-induced coatings, atmospheric correction, and surface resolution (Ramsey and Fink, 1999, 1997a,b; Eisinger et al., 2000). Analysis of the data has found that topographic roughness on the centimeter-scale within the classically defined textural units of silicic flows does show a correlation with the vesicularity.

5) Lava surface textures and volatile content

In addition to remote sensing of lava surface textures, we have continued our laboratory and field studies trying to relate the surface textures of silicic lavas to their volatile contents and their potential to undergo explosive decompression. From a planetary standpoint, identification of the equivalent of block-and-ash type deposits adjacent to scars in the perimeters of dome-like features would point toward silicic magma composition, as would recognition of highly contrasting surface textures. Furthermore, constraining how volatiles are distributed within and escape from erupting magma bodies would greatly assist in the interpretation of eruption mechanisms.

A persistent complication in our attempts to relate surface texture to H₂O content and explosivity was the confounding effect of meteoric H₂O, which tends to mask the true magmatic H₂O signature, particularly in vesicular lavas. Our latest geochemical innovation on this front has been to adapt hydrogen isotope step-heating analyses to distinguish meteoric and magmatic H₂O in glassy lava samples (DeGroat-Nelson et al., 2001). The step-heating method allows us to identify the nature of the H₂O component based on the temperature the H₂O is liberated and its measured D/H ratio. Using this new capability, we were able to show that for two different lava domes, magmatic H₂O increases linearly downward toward the flow interior at a rate of approximately 0.01 wt% per meter (DeGroat-Nelson et al., 2001). The measured magmatic H₂O contents for these lavas extrapolated inward imply that overpressures of 10⁶ Pa may occur 15-20 m below the surface. This is the depth reached by explosion craters found on the surfaces of obsidian flows and also corresponds to the level at which higher magmatic volatile contents (up to 0.5 wt%) were found in cores from a DOE and NSF-funded drilling program through the Inyo domes (Vogel et al., 1989, *Geology*). These gradients suggest that H₂O concentrations high enough to generate pyroclastic flows during front collapse may occur in the upper portions of certain domes.

6) Dike emplacement and volcanic stress states

Besides providing information about magma chamber and eruption processes, lava flows and domes offer indirect evidence of the positions of buried magmatic intrusions, based on the alignments of eruptive vents and associated ground cracks. We have mapped and modeled radial fracture patterns on Venus in order to infer locations (size and depth) of buried magma chambers and estimate relative magmatic and tectonic stresses at the time of dike emplacement (Koenig and Pollard, 1998). We have also explored the relationships between the morphology of a volcanic edifice, the resulting state of stress, and controls on dike emplacement through a combination of field measurements (leveling, GPS, and AMS) at Medicine Lake volcano, CA and Summer Coon volcano, CO, and theoretical analysis (Dzurisin et al., in press; Poland et al., in review-a, b; Poland, 2001; Koenig et al., 1999, 2000). As a volcano grows in size and weight, gravitational processes play an increasingly important role in determining its structural and magmatic evolution (Borgia, 1994, *JGR*). For the large shield volcanoes seen on Mars and Venus, these effects may be particularly important. Volcanic spreading produces a characteristic distribution of structural features, including rifts and grabens related to extension and collapse of topographic summits, and basal thrust faults and folds around the volcano periphery induced by lateral flank displacement. Borgia et al. (2000, *Ann. Rev. Earth Plan. Sci*) formulated an analytical solution that allows us to infer relationships between the thicknesses and rheological properties of volcanic substrate layers based on the geometry and distribution of surface structures, and we have identified new examples of volcanic spreading on Mars, Venus, and Earth (Borgia et al., 2000a,b).

Publications Summary

17 papers published, 2 in press, 3 in review; 40 abstracts; 5 M.S. theses; 3 Ph.D. theses.

Publications

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- Pamela DeGroat - M.S.: "Hydration and degassing of silicic magmas and glasses," 197 p., 1997.
- Christopher Eisinger - M.S.: "Characterizing the composition of silicic lavas using infrared remote sensing," 71 p., 2002.
- James Fowler - M.S.: "The effects of a time-variable extrusion rate on the morphologies of small submarine volcanoes," 80 p., 1997.
- David Lescinsky - Ph.D. "Lava flow morphology: The roles of external confinement and lava-ice interaction," 209 p., 1999.
- Aaron Lyman - M.S.: "The effects of slope on the growth and collapse of lava domes," 115 p., 2001.
- Michael Poland - Ph.D. "Determining the stress regime within a volcanic edifice from igneous intrusions and deformation measurements," 384 p., 2001.
- Wendy Schwarz - M.S. "Europa: Interpretation of dome formation," 40 p., 1999. (Co-advisor)
- Rick L. Wessels - Ph.D. "Remote sensing and tectonic analysis of active volcanoes in continental arcs," 154 p., 1999. (Co-advisor)